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FINAL REPORT

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This is the Final Report of the project. When the work was started it was anticipated that it would run for a number of years, since extensive basic research would be required to attain the objectives. Unfortunately, from our point of view, the decision was made not to extend the funds of the project beyond those appropriated for the first year. As a consequence, it has not been possible to reach the objectives of the project. We have, however, made some progress, and this report is essentially a presentation of those parts of our completed work which we hope may have some permanent value.

The work of the project consisted of three parts:

1. Development of a general theory of organized systems and organized activities. Considerable progress was made in this area. Appendix I of this report gives a formal presentation of the completed portions of this part of the work.

2. Studies of the work of biologists concerning the development of organisms with the hope that this would give us useful insight into programming and into the development of organized activities. Appendix II is a presentation of what we have to contribute along these lines as a consequence of the project work.

3. Work with computer experts of the Syracuse University Research Corporation on the design of computers with the purpose of applying our organization theory to computers, particularly computers used in Navy planes. It was our plan to begin by applying organization theory to microprogramming. By the time of termination of the project, the Project Director had learned quite a bit about computer design and microprogramming, but we did not yet have any useful output.

We regret that the project was terminated and we hope that it will be possible to continue at least parts of the work in the future.

Personnel on the project consisted solely of the Project Director.

APPENDIX 1

THEORY OF ORGANIZED SYSTEMS AND ORGANIZED ACTIVITIES

(Incomplete)

CONTENTS

1. Elements, States, Constraints and Choice

It is the purpose of this paper to try to discover basic concepts and phenomena of organization, and to see how a knowledge of these can be used to get a better understanding of nature.

As a model or prototype of an organized system we shall study the properties of a system consisting of a number, say n, of elements, each element having a number, say L, of different possible states in which it can exist. It is not necessary that the n elements be similar, although they will be in many cases of interest. It is also not necessary that the number or type of states in which the elements can exist should be the same. Furthermore, the numbers n and L need not be finite, nor even countable.

Consider a system which has n distinguishable elements. They may, for example, be distinguishable by their location, or their shape, or their size, or their color. If the i^{th} element of the system has L_i different states in which it can exist, then the total number of different possible states of the system is at most

$$W_M = \prod_{i=1}^{n} L_i \qquad (1\text{-}1)$$

If there are no constraints between the different elements of the system, i.e., if they are all independent, so that the possibility of any state for the general i^{th} element is not affected by the states in which the other elements exist, then W_M in Equation (1-1) gives the actual number of different possible states of the system. We shall call W_M the <u>unconstrained choice of states</u> of the system.

The statement that a system is <u>organized</u> means that there are <u>constraints</u> on or between the elements. If there are constraints on the elements, this means that one or more of the L_i have, in effect, been decreased. If there are constraints between the elements, this means that the elements are not independent of each other. This dependence will rule out those originally possible states of the system which are inconsistent with the constraints. It follows that the choice of possible states of the organized system is less than W_M. The magnitude of the reduction in choice is one of the most significant measures of the organization.

Let us consider an example of how the constraints of a physical system can reduce choice. Consider an electrostatic system, and let us consider the choice of possible potential distributions in the system. If there were no constraints on the system of which we were aware, we would have to start with the possibility that every point in space had a continuous range of possible potentials extending from $-\infty$ to $+\infty$. Let us first restrict the problem to the region R bounded by the surface S in Fig. 1. This reduces the elements of the system to the points in the region R. The choice is still infinite.

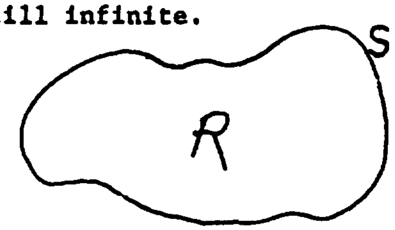

Fig. 1

Let us next require that the potential obey Laplace's equation in the region R and on the surface S. This is an enormous reduction in choice of potential distributions, because it rules out all distributions which are not continuous functions and do not have second derivatives, and whose second derivatives do not obey Laplace's equation. The choice, however, is still infinite. As a final constraint, let us specify the distribution of the potential on the

boundary S. If the specified boundary conditions are consistent with Laplace's equation, then the choice is reduced to unity; namely, the solution of the problem. If the boundary conditions are not consistent with Laplace's equation, the choice is reduced to zero.

A constraint of special interest for us is the limitation of bandwidth in communication systems. Suppose we have a system of signal waveshapes as a function of time. If there are no constraints, the uncountably infinite number of points on the axis of time are the system elements of the signal waveshapes. If, however, the bandwidth is limited to a finite range, the sampling theorem[1] tells us that the number of system elements is limited to the countably infinite number of sample points. This is at first surprising since there are apparently an uncountably infinite number of frequencies in the finite but continuous range of allowed frequencies. However, in the specification of frequency range, the implicit constraint is added that the function is Fourier transformable, which accounts for the reduction to countability.

The sampling theorem of information theory states "If a function contains no frequencies higher than W cycles per second, it is completely determined by giving its ordinates at a series of points spaced $\frac{1}{2W}$ seconds apart, the series extending throughout the time domain." A section of duration T of such a function will then contain

$$n = 2TW \tag{2}$$

sample points, i.e., effectively distinguishable elements. We may also say that a system of bandwidth W has an effective limit of resolution in time of $\frac{1}{2W}$.

In all real systems there are limits of resolution which reduce the effective number of distinguishable elements and the effective number of distinguishable states per element to a discrete and finite set even in continuous systems.

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[1] Ref. [1] p. 67.

The actual limit of resolution, is due to that cause which is responsible for the coarsest resolution. In the hypothetical absence of that cause, some other cause would still limit the resolution, but at a finer value. Limited resolution of both elements and their states is caused by deterministic constraints and by noise. In the particular case of a high gain amplifier, the actual cause in limiting resolution of distinguishable elements is usually bandwidth, while the actual cause in limiting resolution of distinguishable states per element is usually noise.

2. Stochastic Constraints and Entropy

The constraints which we have discussed so far may be called deterministic constraints. They include the forces between physical objects and, in fact, most of the laws of classical physics, excepting those in which statistical mechanics is involved. They would include bandwidth limitation, as already mentioned. Their effect on choice is to specify that certain choices are ruled out, i.e., they are not possible.

An equally important class of constraints are the stochastic constraints. Their effect is not to rule out choices, but to affect their probability of occurrence. In a formal sense, deterministic constraints are a special case of stochastic constraints. In a system which is organized completely by deterministic constraints, there is unit probability for a particular choice (or result) and zero probability for all other choices.

Those laws of quantum physics which are expressible in terms of the wave function are stochastic constraints. Many stochastic constraints are expressions of the incomplete knowledge on the part of the observer concerning the initial conditions. In some such cases, a complete knowledge of the initial conditions would completely determine the final results. On the other hand, the presence

of random noise in a system represents a constraint which is intrinsically stochastic.

A most important measure of stochastic systems is entropy. If a set $\{p_i\}$ of probabilities satisfies the equation

$$\sum_i p_i = 1 \tag{3}$$

then

$$H = -\sum_i p_i \log p_i \tag{4}$$

is defined as the <u>entropy</u> of the set of probabilities[2].

The same formal definition of entropy can be extended to apply to the states of an element or the states of a system. For example, suppose that the L_i different possible states of the i^{th} element are equally probable. Then

$$p_j = \frac{1}{L_i} = \text{probability of the } j^{th} \text{ state} \tag{5}$$

and

$$H_i = -\sum_{j=1}^{L_i} p_j \log p_j = \log L_i = \log(\text{choice}) \tag{6}$$

Entropy equals log(choice) only when all the different possible choices are equally probable. Any other distribution of probabilities will give a smaller entropy. Accordingly, we shall consider the assignment of a set of probabilities to the states as a stochastic constraint, if the probabilities are not all equal.

If a system were made up of n similar elements, between which there were no constraints, then there would be a choice of

$$W_M = L^n \tag{7}$$

different possible states of the system. If these states were all equally

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[2]The numerical value of H will depend on the base used for the logarithms.

probable, then the entropy of the system would be

$$H = \log W_M = n \log L = \log(\text{choice}) \qquad (8)$$

We note that the entropies of the system elements are additive when there are no constraints between them. Every constraint, whether acting on individual elements or between elements, will reduce entropy[3]. The change in entropy is probably the most important measure of the effect of a constraint[4].

3. Organization as Negentropy

From the point-of-view of entropy, we may look upon the organization of a system as a reduction in its entropy. We can measure the organization in units of entropy and we say that the amount of organization is equal to the reduction in entropy caused by the constraints which constitute the organization. Accordingly, we say that organization is measured in units of negative entropy, which term, following Brillouin, we contract to negentropy. Thus, uncertainty is measured in units of entropy, and organization is measured in units of negentropy.

4. Ambiguity and Noise

If a system is organized to the extent that each system element is in the particular state prescribed for it, then the probability that the system is in its prescribed state is unity and the probability that it is in any other state is zero. The entropy of the system is then zero and no further organization of this system is possible.

In some organized systems, it may not be desired that the entropy be reduced to zero. For example, a manufactured clock may be considered completely organized irrespective of the time indicated on its face. In some cases, one can eliminate the residual entropy by redefining all these equally desirable states as a single

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[3] Ref. [2] p 17-19

[4] The same measure will also apply to the effect of deterministic constraints. The states which are ruled out by the constraints are assigned zero probability. All allowed states are assigned equal probability in the absence of stochastic constraints.

state, but often that is not practical. In many cases, however, the residual entropy of an organized system represents, what is in principle at least, a defect in organization. This is true in the important case when there is ambiguity (noise) present.

We shall divide the conditions in which ambiguity is present into two categories:

(1) When one or more of the elements of a system are not in their prescribed states, we say that state noise or amplitude noise is present[5]. We also use these terms to describe the situation in which there is ambiguity as to which states the elements are in, or the situation in which the characteristics of the states are not those prescribed.

(2) When there is an ambiguity or probability of misinterpretation as to which element of a system is which, we ribe the condition by saying that identity noise or location noise is present[6]. We also use the term identity noise to describe the situation in which an element, although unambiguously recognized, does not have the characteristics which are prescribed for it.

Example (a)

Radar Signal Organized by the Target

As an example of amplitude noise, we cite the case of the signal which is displayed on a radar screen (See Fig 2) the signal having been organized by the scattering of a transmitted electromagnetic wave by one or more targets. The organized

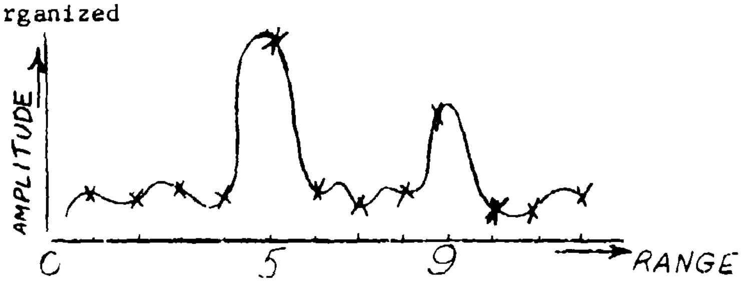

Fig. 2

Radar Signal

Sample values indicated by X.

[5] The term "amplitude noise" is used when the possible states of each element form ordered sets.

[6] The term "location noise" is used when the elements of a system form an ordered set.

signal is used to determine the range (distance from observer) and size of the targets. In this case the noise arises in the receiver and is added (as a complex quantity with amplitude and phase) to the signal coming from the target. The elements of the organized signal in Fig. 2 are the sample points (the signal has limited bandwidth) and their possible states consist of the continuous range of possible amplitudes at the sample points. It is known from the characteristics of the system that the noise amplitude at each sample point has a probability density

$$p(N)dN = \frac{2N}{\langle N^2 \rangle} e^{-\frac{N^2}{\langle N^2 \rangle}} dN \qquad (9)$$

where N is the noise amplitude and $\langle N^2 \rangle$ is the ensemble average of its square. The phase of the noise is uniformly distributed from zero to 2π. Figure 2 is a plot of the resultant amplitude when the complex quantities representing signal and noise are added. The figure thus illustrates amplitude noise[7]. There appear to be targets at ranges of 5 and 9 miles. Later on we shall calculate quantitatively the effect of the amplitude noise on the organization of the signal.

Example (b)

Doppler Spread of a Spectrum

As an example of location noise we cite the broadening of spectral lines due to the doppler effect caused by the thermal motion of the radiating atoms. As a consequence of doppler broadening, two or more spectrum lines may overlap and it may not be possible to separate (resolve) them.

Example (c)

The Spread Function of a Photographic Plate

Another example of location noise is the spread function of a photographic plate. If the system of lenses which forms an image in a photographic plate is

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[7] The use of the term "amplitude" in amplitude noise refers to a state magnitude and the magnitude is not necessarily the amplitude of a complex quantity, although it happens to be in this example.

so good that it may be considered free of diffraction and aberration, so that a point on the object is transformed into an optical point in the image, the image on the photographic plate of a point in the object will still have a finite spread. The reason for this is that there is a stochastic component in the photographic process which spreads the image point on the plate[8]. The distribution of density on the plate as a function of distance from the light point in the image is called the spread function of the plate. It is the resultant of the effects of what is almost an ensemble of photons, so that it is largely determined by the expectation values of the process[9] and to that extent it is almost deterministic. Since, the number of photons involved, however, is finite, there are always fluctuations present in any particular experimental example of the spread function. The deterministic or average values of the spread function have the same effect on image resolution as a reduction in effective spatial bandwidth such as would be caused by diffraction or aberration.

Actually, the observed doppler spread of a spectrum line is likewise principally the observation of the expectation of the doppler effect in what is essentially an ensemble of radiating atoms. The noise in the radar signal example, however, is much more like the effect of an individual stochastic event, since the expectation of the noise can be, and for all practical purposes is, subtracted out in the observation process. On the other hand, if the amplitude noise in Fig. 2 became so large that one of the noise peaks were mistaken for a target, then the amplitude noise would give rise to identity noise. This would be an example of an individual stochastic event in location or identity noise in the observation. Of course, there would also be errors made in estimating the signal amplitudes returned by the actual targets. We note that in systems in which both the distinguishable elements and their states are in ordered sets, a small amount of

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[8]Ref. [3] p. 298.

[9]This is an oversimplification since the real process is non-linear.

location noise can be interpreted as amplitude noise and may not cause ambiguity. This is illustrated in Figure 3.

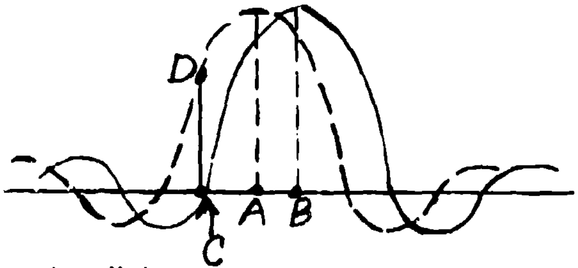

Fig. 3

$\overline{AB}$ = magnitude of location noise.

$\overline{DC}$ = magnitude of equivalent amplitude noise at the next sample point (Note that it is proportional to the signal).

5. White Gaussian Noise

There is one type of noise which in linear and quasi-linear systems represents the essence of disorganization. This is white gaussian noise. White gaussian noise is a type of amplitude noise. Identity noise and location noise, when the effect of the latter is to cause ambiguity between elements of a system, are of an essentially non-linear nature[10]. White gaussian noise is a stochastic disturbance (of the organization of a system) having the following three properties:

(1) It has a gaussian distribution of amplitudes, i.e.

$$p(N)\,dN = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{N^2}{2\sigma^2}} \tag{10}$$

$$\text{where } \sigma^2 = \int_{-\infty}^{+\infty} N^2 p(N)\,dN \tag{11}$$

while N is the noise amplitude and p(N) is its probability density.

(2) The noise amplitudes of the different elements are statistically independent.

(3) σ^2 is the same for every element.

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[10] Location noise, when it is so small in magnitude that it causes no ambiguity between system elements, is not identity noise. In this case it may have the effect of amplitude (state) noise as previously noted.

For a given amount of noise energy and a given number of system elements, white gaussian noise has the maximum possible entropy.

White gaussian noise also has the remarkable property that it has a statistically independent gaussian distribution of the same σ^2 in any orthonormal basis system of vectors in function space[11]. This mathematical fact is the basis of the equipartition law in statistical mechanics, since the thermal motion of moelcules has the characteristics of white gaussian noise.

In the real world, white gaussian noise arises as a consequence of the central limit theorem and the breakdown of constraints between system elements in the superposition of large numbers of independent effectively stochastic distrubances. In the particular case of thermal motion, there are no stochastic constraints between system elements because of the random nature of the stochastic coupling between degrees of freedom, and the gaussian distribution is a consequence of the central limit theorem.

Our original definition of entropy was

$$H = -\sum_i p_i \log p_i \tag{12}$$

However, when a system has a continuous distribution of states as is the case for white gaussian noise, this definition is modified to

$$H = -\int_a^b p(x) \log p(x) dx \qquad (13)^{12}$$

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[11]Reference [4] p. 232.

[12]Reference [1] Chap. IV. The form of Eq. (13) neglects what amounts to an infinite additive constant in the entropy of a continuous distribution. It is reasonable to do this only because in all practical applications of the entropy of a continuous distribution, such as in Eq. (17), the infinite constant is cancelled by the subtraction of the identical constant.

where the possible states of the system are specified as values of x and the range of x is from a to b. It is easily shown[13] that the entropy of white gaussian noise is $\log\sqrt{2\pi e\sigma^2}$ per system element. The noise amplitudes of the different system elements in white gaussian noise are statistically independent. Therefore, if the system has n elements, the total entropy of the white gaussian noise is

$$H = n \log\sqrt{2\pi e\sigma^2} \qquad (14)$$

6. The Effect of Amplitude Noise on Choice of States

We can use Equation (14) to obtain an intuitive concept of the effect of noise on choice. Suppose we have a communication system having signals of duration T and bandwidth B, whose only other constraint is that the mean square amplitude of the signals (i.e., the average power) is prescribed as S^2. The instantaneous amplitude may be either positive or negative. According to the sampling theorem, these signals will have 2TB sample points and therefore 2TB independent elements. We will consider the case in which $2TB \gg 1$. Now the entropy of white gaussian noise is the maximum of that of all ensembles of signals of the same mean square amplitude. Since the set of possible signals of the foregoing communication system has no constraints other than bandwidth, duration and average power, we shall consider that its entropy is the same as though it were a random noise ensemble[14]. Therefore, prior to making a selection of one particular signal, the entropy of the set is

$$H_S = 2TB \log\sqrt{2\pi e S^2} \qquad (15)$$

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[13] Reference [1] pages 131-133

[14] This is based on the assumption that for signals of the same average power, as 2TB becomes very large, those signals whose wave shapes approximate white gaussian noise will ultimately greatly outnumber all others combined. This appears to be a reasonable extrapolation of results which have been derived in information theory. See Ref. [2] pages 15-16.

Suppose there is also white gaussian noise in the system, with average power σ^2. Now the superposition of two gaussian ensembles gives another gaussian ensemble with a mean square value equal to the sum of those of the superimposed ensembles. Therefore, prior to the selection of a signal, the entropy of the signal plus noise ensemble is

$$H_{S+N} = 2TB \log \sqrt{2\pi e(S^2+\sigma^2)} \tag{15A}$$

After making the selection of a particular signal, the entropy of the system is reduced to that of the noise, namely

$$H_N = 2TB \log \sqrt{2\pi e\sigma^2} \tag{16}$$

The negentropy of the organized signal in the presence of the noise is therefore

$$H_{S+N} - H_N = 2TB \log \sqrt{2\pi e(S^2+\sigma^2)} - 2TB \log \sqrt{2\pi e\sigma^2} = 2TB \log \left(1 + \frac{S}{\sigma}\right)^{1/2} \tag{17}$$

Comparing Eq. (17) with Eq. (8) we see that the effect of the noise is to reduce the number of states per element to the finite effective number $\frac{S}{\sigma}$, if $\frac{S}{\sigma} \gg 1$. In other words, σ is the effective spacing between distinguishable states. In the absence of noise, the theoretical number of states per element is uncountably infinite. The latter fact is related to the infinite constant mentioned in the footnote to Eq. (13).

In all organized systems of the real world in which the states of an element have a continuous range of possible values, there is effectively always noise present[15] so that the negentropy measuring the organization is finite.

7. Coherence and the Effects of Location Noise

The word coherence is very significant in physics and in communication theory. Things which are coherent are parts of, or are expressions of, the same individuality. Their characteristics arise from the same source. Knowledge of one is

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[15] Of course, the noise need not be white gaussian.

sufficient to determine the other. Things which are partially coherent are partially dependent[16] In accordance with this terminology, we shall use the degree of coherence to describe the degree of dependence between the parts of an organized system. If a system is completely organized, its parts are completely coherent.

A good mathematical example of an entity whose parts are coherent is a function which can be expanded in a Taylor series about the point P (see Fig. 4), the expansion holding everywhere in the region R. If the values of this

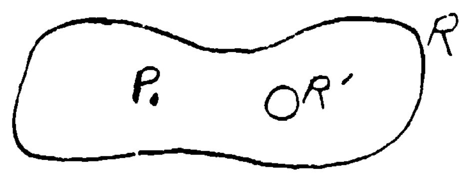

Fig. 4

function are known in any small region, R', no matter how small, the function is completely determined everywhere in R. The function is therefore coherent in the region R. The derivatives of all order in the Taylor series may be considered to represent the set of system elements of the function. They are a countably infinite set[17].

Both amplitude and location noise will tend to reduce coherence. We shall find it very instructive at this time to consider some effects of location noise. In Example (c) of Section 4 we pointed out that location noise causes a unit impulse to spread to a function of finite width; which, following photographic terminology, we shall call the spread function. The effect of the spread function is to cause a loss of resolution very similar to that caused by a bandwidth limitation. <u>This limits the smallness in size of the parts of a system which can be organized</u>.

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[16] In optics, coherence refers to the dependence between the instantaneous respective amplitudes and phases of two disturbances or of parts of the same disturbance.

[17] The set of orthogonal functions in an orthogonal function expansion of the original function in the region R would represent an alternative set of system elements of the same system. The transformation of the representation of a system from one set of system elements to another is often very useful.

Let us next consider the same system represented in its Fourier transform domain. The elements of the system are now its frequency components and we turn our attention to the effect of location noise of these frequency components. The doppler spread of a spectrum, such as mentioned in Example (b) of Section 4, would represent location noise in the frequency domain. Consider a single frequency component which is spread by location noise in the frequency domain to cover a frequency range Δf. In the absence of location noise, if the amplitude and phase of the frequency component were known at one point in time, it would be completely known for all time. However, as a consequence of the location noise, if the amplitude and phase of the component are known at one point, they gradually become uncertain as one leaves that point and become completely uncertain for distances from the point exceeding $\frac{1}{\Delta f}$. If the value of Δf is the same for all frequency components[18], we can say that location noise limits the coherence range of the signal (or other system which can be represented as a continuous function) to a maximum value of $\frac{1}{\Delta f}$ [19].

Consider a one dimensional system which has location noise in the time domain causing a spread function of effective width Δt, and which has location noise in the frequency domain causing a spread function of effective width Δf. Then the

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[18] This would usually be true for narrow band systems such as a modulated carrier or a wave packet in quantum mechanics.

[19] The effect of the resistive component of a tuned circuit is analogous to the introduction of location noise at the resonant frequency, f_0, and its amount Δf is the same as the bandwidth caused by the resistance. The effective coherence range is $\frac{1}{\Delta f}$, and this is

$$\frac{f_0}{\Delta f} = Q$$

cycles at the tuning frequency.

system cannot be organized in parts smaller than Δt nor larger than $\frac{1}{\Delta f}$. <u>The number of effective elements of the organized system can therefore not exceed</u>

$$\frac{1}{\Delta f \cdot \Delta t} \qquad (18)$$

For an n-dimensional system, it is fairly obvious that there would be a factor of the same form as Eq. (18) for each dimension. This is a significant result.

If the above one dimensional system is limited to a bandwidth B which is less than $\frac{1}{\Delta t}$, then bandwidth limitation rather than location noise limits the smallness of organization and the number of effective elements of the organized system cannot exceed

$$\frac{B}{\Delta f} \qquad (19)$$

8. <u>Requirements for Organizing a System: Information, Energy and Transducers</u>

We next consider the requirements for organizaing a system. The system may be either a static structure or an operating mechanism. For example, we would usually consider a building as a static structure. Likewise, an automobile on display in a showroom is a static structure. On the other hand, a running automobile or a living organism is an operating mechanism. In order to make an organized system, one must somehow obtain its elements and put them in their proper states. Let us see what is required to do this. For example, in order to make an automobile, one must

(a) Have a specification of the automobile to be made.

(b) Know where the parts or raw materials are available for purchase.

(c) Have the necessary facilities to process them into the organized automobile.

(d) Have the necessary money to pay for the purchase and manufacturing.

This description of the organization of an automobile describes the requirements for so doing in the socio-economic world. The description is incomplete, but is sufficient to illustrate certain general principles. In order to make an automobile in the socio-economic world, one needs information, available raw materials, a manufacturing facility and money to pay for everything. The analogous requirements to make an organized system in the physical world are information, available raw material, transducers and available energy[20].

A very instructive example of what is involved in organizing a system is provided by a "matched" filter as used in radar. In this case a pulse of electromagnetic energy of some specified wave shape s(t) is radiated from a transmitter. If some of the energy in this pulse is scattered or reflected by a target and returned to a receiver at the same location as the transmitter, then the detection of the returned energy is evidence of the existence of the target. Measurement of the time delay, call it t_0, between pulse transmission and reception, becomes a measurement of the distance between the target and the radar, since the velocity of propagation of electromagnetic energy is known. Figure 5 shows a diagram of the waveshape of the transmitted radar pulse, as well as that of the received pulse which enters the radar receiver. The radar receiver behaves as a matched filter. A great many details of the radar equipment which are not pertinent to our discussion are eliminated from Fig. 5.

If

$$S(\omega) = \int_{-\infty}^{+\infty} s(t)e^{-j\omega t}dt = |S(\omega)|\ e^{j\phi_s(\omega)} \tag{21}$$

is the fourier transform of s(t), then the matched filter for s(t) will be a linear transmission system having a frequency transmission characteristic

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[20]The term <u>available energy</u> is used here in the technical sense.

$$Y(\omega) = |Y(\omega)|e^{j\phi_Y(\omega)} = |S(\omega)|e^{-j\phi_s(\omega)} = S^*(\omega) \qquad (22)$$

which is the complex conjugate of $S(\omega)$. The received signal, $\underline{a}\ \underline{s}\ (t-t_0)$, will have a fourier transform

$$\underline{a}\int_{-\infty}^{+\infty} s(t-t_0)e^{-j\omega t}dt = \underline{a}S(\omega)e^{-j\omega t_0} \qquad (23)$$

The output of the matched filter will then be

$$\overline{s}(t) = \frac{a}{2\pi}\int_{-\infty}^{+\infty} Y(\omega)\cdot S(\omega)e^{-j\omega t_0}e^{j\omega t}d\omega = \frac{a}{2\pi}\int_{-\infty}^{+\infty}|S(\omega)|^2 e^{j\omega(t-t_0)}d\omega \qquad (24)$$

Since the fourier transform of the power spectrum is the autocorrelation function[21], Eq. (24) tells us that the output signal has the wave shape of the autocorrelation function of $s(t)$, and that it is delayed by a time t_0. Furthermore, if white gaussian noise is introduced at the input, as usually occurs in a high gain amplifier, and if the white gaussian noise has a noise power per unit bandwidth of $4\pi k^2$, then it is easily shown[22] that the signal-to-noise ratio

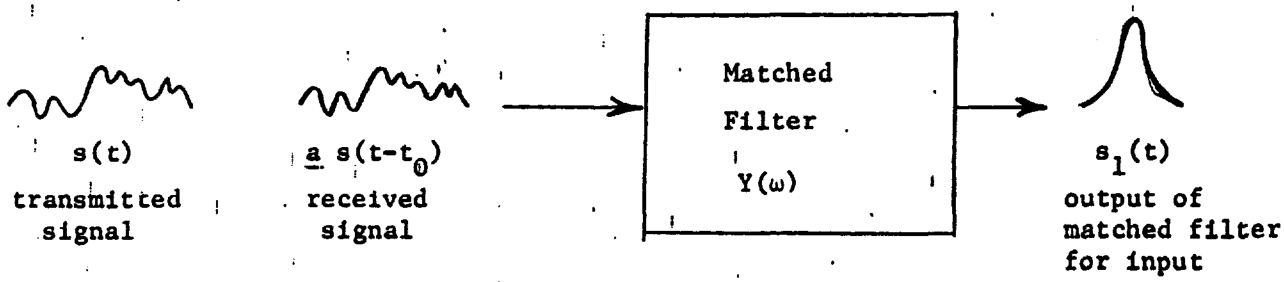

Fig. 5

$\underline{a}\ s(t-t_0)$

Radar Receiver as a Matched Filter. (Radar signals are modulated carriers. The envelope waveshapes are shown here.)

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[21] Ref. [1] page 247

[22] Ref. [1] page 232. The value of noise power per unit bandwidth as used in the present paper is twice as large as it would be if we considered negative frequencies as distinct from positive frequencies. The term bandwidth as we have used it refers to positive frequencies only.

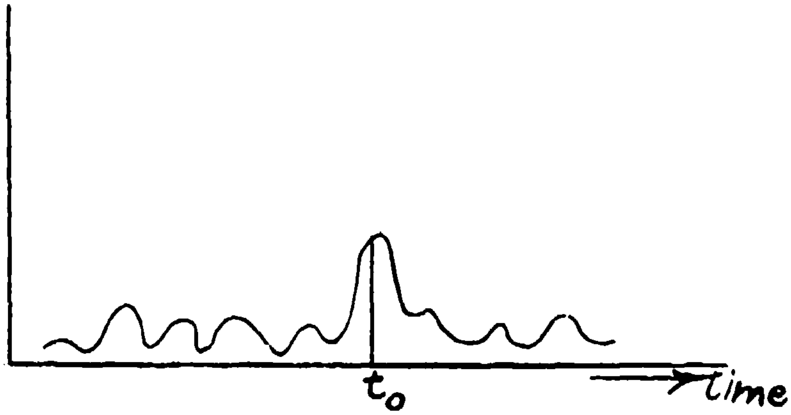

Fig. 6

Display of Received Radar Signal in Background of Noise. (Pulse leaves transmitter at t = 0.) The pulse at t_0 has the waveshape of the autocorrelation function of the transmitted pulse.

in the output will have a maximum at t_0, and its value there will be

$$\left\{\frac{\frac{a^2}{2\pi}\int_{-\infty}^{+\infty}[S(\omega)]^2 d\omega}{2\pi k^2}\right\}^{1/2} = \left\{\frac{2 \text{ Total energy of } \underline{a}\ \underline{s}(t)}{\text{Noise power per unit bandwidth}}\right\}^{1/2} \qquad (25)$$

Figure 6 shows the display of a received radar signal[23].

Since a radar transmitter is usually limited in peak power, the transmitted pulse shape of a long range radar is usually relatively long so as to get a lot of energy into the pulse. It is also common to put a great deal of wave shape detail in the pulse so that among other reasons, it will include considerable high frequency energy in its waveshape in order to get a sharp autocorrelation function.

The purpose of the matched filter is to organize the received signal[24] so that it gives the maximum probability of detection of the existence of a target,

[23]Since a radar display shows the envelope of a modulated carrier, the noise in Fig. 6 is the envelope of white gaussian noise and has the probability density indicated in Eq. (9)

[24]The received signal is the raw material which is organized by the matched filter.

and the greatest accuracy in determining its range. The frequency components[25] of the received signal are the system elements which are organized by the matched filter. These are constrained by the matched filter so that they all have zero phase (have maximum value) at time t_0. This gives the maximum possible signal amplitude at t_0 for a given signal energy. The constraint on the frequency components of both the signal and noise imposed by the relation

$$|Y(\omega)| = |S(\omega)| \tag{26}$$

coupled with the phase constraint, gives the maximum possible signal-to-noise ratio (on the ensemble average). In other words, the matched filter gives the most effective possible organization of the signal for the purpose of target detection and accuracy of range determination.

In the natural world it takes energy to do the things which it is desired to accomplish. To make this energy effective, it must be organized by a transducer, such as the matched filter in the foregoing example. In order to design the proper transducer, one requires detailed information about the elements of the energy, i.e., analogous to the waveshape or magnitudes and phases of the frequency components in the matched filter case.

In thermodynamics, detailed information of the energy elements is necessary in order to have a transducer to make the energy effective for the purposes at hand. However, it really requires both the information and the existence of the transducer to make the energy "available", i.e., effective. In thermodynamics, entropy measures the lack of information about the states of the energy elements[26].

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[25] It would be more accurate to say the Fourier series components, since the matched filter is usually matched to the waveshape of a single pulse as shown in Fig. 5 and is not matched to the chain of repeated pulses transmitted by the radar.

[26] Ref. [5] page 160 states that "entropy measures the lack of information about the actual structures of a physical system."

9. Information, Organization and Thermodynamics

According to information theory[27], the amount of information in a message concerning an event is

$$\log \frac{p_2}{p_1} \tag{27}$$

where p_1 is the probability of the event before the message is received, and p_2 is the probability of the event after the message is received. For example, suppose that an observation is made of the state of a molecule, and the observation indicates that the molecule is in state A. Suppose also that the molecule is actually in state B, which may or may not be the same as A. Then p_1 in Eq. (27) was the probability that the molecule was in state B, prior to the observation and p_2 is the probability that the molecule is in state B after the observation is made[28]. If there is no noise in the observation system, so that all observations are known to be correct, then $p_2 = 1$ and the amount of information in the message, according to Eq. (27), is

$$-\log p_1 \tag{28}$$

If the possible results of an observation are a set $\{i\}$ and if the observation is noiseless, then the ensemble average of the amount of information in an observation of this kind is clearly

$$-\sum_i p_i \log p_i \tag{29}$$

which is identical with the entropy of the set of probabilities of the possible results of the observation.

Whether noise is present or not, the amount of information indicated by (27) cannot exceed that given by (28). It is also noteworthy that when the

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[27] Ref. [1] page 4

[28] We note that p_1 and p_2 in Eq. (27) are the <u>a priori</u> and <u>a posteriori</u> probabilities of the event which actually takes place in the world, regardless of whether or not the message reports the event correctly.

message is wrong, the amount of information in the message is negative. The ensemble average of the information per message, however, cannot be negative, regardless of how noisy the observation system may be.

Any noiseless observation reduces the entropy of the set of probabilities of the possible results to zero. The observation, therefore, represents a negentropy of amount (29). Information, entropy and negentropy are expressible in the same units. The unit is physically dimensionless, but depends upon the base used for the logarithms. When $\log_2$ is used, the unit is called a bit. In engineering and chemical thermodynamics, entropy is usually expressed in units of $\frac{\text{energy}}{\text{temperature}}$. One unit of entropy in cgs degrees Kelvin units is $\frac{1}{k}$ bits, where $k = 1.38 \times 10^{-16}$ ergs/degree. The numerical value of the entropy or negentropy representing the disorder or order, respectively, of the molecules in macroscopic physical systems is thus orders of magnitude larger than quantities measuring information or organization in man-made systems.

Brillouin [5] has dealt with relations between information, negentropy and physical entropy in detail[29]. The following conclusions, taken from his book[30], are pertinent to our work:

(A) Information can be changed into negentropy, and vice versa. If the transformation is reversible, there is no loss, but an irreversible transformation always corresponds to a loss.

(b) Any experiment by which information is obtained about a physical system produces, on the average, an increase of entropy in the system or in its surroundings. This average increase is always larger than (or equal to) the amount of information obtained. In other words, information must always be paid for in physical negentropy, the price paid being larger than (or equal to) the amount of information received.

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[29] Claude Shannon [7], [8], [9] is the architect of modern information theory. His work is fundamental to that in many of the references we have quoted and to this paper. The realization that entropy is an expression of missing information goes all the way back to Boltzmann according to Brillouin [5] and Woodward [10].

[30] Slightly paraphrased from page 184.

An observation is always accompanied by an increase in entropy, and thus involves an irreversible process.

(C) The smallest possible amount of negentropy required in an observation is one bit[31].

The foregoing discussion applies to available and unavailable energy in thermodynamics. An ideal gas in thermal equilibrium, all at a given temperature, is a system in a condition of maximum entropy. In our terminology it is completely disorganized. Its energy consists of the kinetic energies of its molecules. If there are N molecules in the gas, then there are 3N independent system elements in the system; namely, the x, y and z components of the velocities of every molecule. The probability density of the amplitude of each system element is gaussian, for example, for each molecule

$$p(v_x)dv_x = \sqrt{\frac{m}{2\pi kt}}\, e^{\frac{-mv_x^2}{2kT}}\, dv_x \qquad (30)^{32}$$

Since the velocity components of the different molecules, as well as the velocity components of the same molecule, are all stochastically independent and are all gaussian with the same σ^2, the system is of the form of white gaussian noise. It is therefore in a condition of maximum entropy, as already stated. The gas has no available, i.e., organized, energy. If there were any organized energy present, it could, in principle at least, be converted into whatever form is desired, provided that the nature of the organization were known and that a suitable transducer were at hand. It is, therefore, reasonable to say that <u>organized energy is "available energy"</u>.

Next, suppose that the ideal gas consists of two separated parts, the first part at temperature T_1 and having N_1 molecules, while the second part is at temperature T_2 and consists of N_2 molecules. The gas now does not represent white gaussian noise, since the amplitude distributions of $3N_1$ system elements

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[31]Brillouin attributes this result to Szilard [6].

[32]Ref. [11] page 83.

have a σ^2 of $\frac{kT_1}{m}$, while the $3N_2$ have a σ^2 of $\frac{kT_2}{m}$. This system is therefore not at maximum entropy and it does have some organization i.e., negentropy. The numerical value of the negentropy is, using Eq. (14),

$$3(N_1 + N_2) \log \sqrt{\frac{2\pi ek}{m} \frac{N_2T_2 + N_1T_1}{N_1 + N_2}}$$

$$- 3N_1 \log \sqrt{\frac{2\pi ekT_1}{m}} - 3N_2 \log \sqrt{\frac{2\pi ekT_2}{m}} \tag{31}$$

For example if

$$N_1 = N_2 = \frac{N}{2}$$

and $\quad T_1 = 300$

while $\quad T_2 = 400$

then the negentropy is

$$\frac{3N}{2} \log \left[\frac{T_1 + T_2}{2}\right] - \frac{3N}{4} \log T_1 - \frac{3N}{4} \log T_2 = \frac{3N}{2} \left\{\log 350 - \frac{1}{2} \log 400 - \frac{1}{2} \log 300\right\}$$

$$= \frac{3N}{2} \left\{0.01487\right\} \text{ bits.} \tag{32}$$

If we rewrite Eq. (32) in the form

$$\frac{3N}{2} \log \sqrt{\frac{2\pi ek}{m} \frac{T_1 + T_2}{2}} - \frac{3N}{4} \log \sqrt{\frac{2\pi ekT_1}{m}} - \frac{3N}{4} \log \sqrt{\frac{2\pi ekT_2}{m}}$$

$$= \frac{3N}{2} \log \sqrt{\frac{2\pi ek}{m} \frac{T_1 - T_2}{2}} \tag{33}$$

we see that the available energy is

$$\frac{3N}{2} \cdot \frac{k}{2} \left(\frac{T_1 - T_2}{2}\right) \tag{34}$$

since the negentropy is numerically equal to the amount of entropy that would be generated if the available energy were transformed into heat. Equation (34) agrees with the classical result obtained in thermodynamics.

Let us next investigate why the thermal energy of an ideal gas which is all at the same temperature cannot be converted into useful form. In order to design a transducer that would convert the unorganized thermal energy into a desired organized form, it is necessary to know the position and velocity of every molecule. To get this information according to the above quotations from Brillouin, we would use up more negentropy than the entropy of the gas. Since this operation is all taking place at the same temperature, we would use up more organized energy in obtaining the information[33] than we could convert from thermal energy into organized form. The thermal energy of an ideal gas which is all at the same temperature is, therefore, properly called unavailable.

The situation is different when the gas is divided into two parts at different temperatures. In the latter case, there is available energy. In order to know what transducer is necessary to convert this available energy into useful form, the information about the state of the system which is required is a measurement of the respective temperatures of the two parts. The energy required to do this is very small in comparison with the energy which is available as a consequence of the temperature difference. Available energy can be turned into useful energy only when the information describing the organization which makes the energy available has (much) less negentropy than the physical negentropy corresponding to the available energy.

10. Significance of E/kT and Woodward's R

It is shown in statistical mechanics[34] that a small system which is in thermal equilibrium, with (or is part of) a large system at temperature T will have a probability of having an energy E_n given by the formula

[33] We note that once the information is obtained, the thermal energy may be considered completely organized. While it would then be possible, theoretically, to build a transducer to convert the energy into any desired form, the practical construction of such a transducer is still completely out of the question. Even if it could be built, however, the energy that could be obtained from it is less than the energy used in determining the position and velocity of every molecule.

[34] Ref. [11] p. 79

$$P(E_n) = Ae^{-E_n/kT} \qquad (35)$$

This is the famous canonical distribution of Gibbs. Equation (35) applies to quantized systems. The corresponding formula for classical systems is

$$p(E)dE = Be^{-E/kT}dE \qquad (36)$$

One of the methods of showing that the thermal motion of a classical ideal gas has the mathematical characteristics of white gaussian noise is based on Eq. (36). An interesting thing about Equation (36) is that it holds regardless of the number of degrees of freedom in the small system, and regardless of the nature of the energy (electrical or mechanical, kinetic or potential, etc.) so long as there is thermal equilibrium. Equations (35) or (36) apply to all physical systems in thermal equilibrium and are not limited to ideal gases.

The derivation of Eqs. (35) and (36) is based in part on the physical fact that the probability density of states for a system in thermal equilibrium is a function only of the energy. This is true both in classical[35] and quantum[36] mechanics. An alternative derivation of the distribution function for the thermal motion of an ideal gas could be based on the central limit theorem and the breakdown of constraints between system elements in the stochastic interaction between loosely coupled systems. We hope later to use this to gain insight into the intrinsic nature of energy.

The analogue of E_n/kT in an information transmission system is

$$\frac{R}{2} = \frac{\text{Total signal energy}}{\text{Noise power per unit bandwidth}} \qquad (37)$$ [37]

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[35] Ref. [11] p. 12

[36] Ref. [11] p. 20

[37] Referring to Eq. (30) we see that the analogue of the mean noise energy per system element is kT/2. Taking into account that there are independent in-phase and quadrature elements at a given frequency, the analogue of noise power per unit bandwidth is kT. The temperature of a physical system is thus the analogue of noise power per unit bandwidth.

The symbol R was introduced by P. M. Woodward[38], who first showed its pivotal importance in information transmission. Comparing Equations (37) and (25), we see that R is the signal-to-noise energy ratio at the output of a matched filter. R, like $\frac{E_n}{kT}$, is, except for a normalization constant, proportional to the logarithm of the probability that the signal (or system organization) is a noise fluctuation, regardless of the signal waveshape[39].

$\frac{R}{2}$ and E_n/kT are completely analogous only if E_n is a single organized (quantum) state[40]. If the energy E_n is transformed into thermal energy at the temperature T, this creates an increase in entropy of amount E_n/kT. Therefore, the negentropy of the organized state is E_n/kT. On the other hand, the negentropy represented by R is numerically equal to the maximum entropy that could be generated by transforming the signal energy into white gaussian noise. If 2TB is the number o sample values which are available in which to express the signal, then according to Eq. (17), the negentropy represented by R is

$$TB \log\left(\frac{R}{2TB} + 1\right) \qquad (38)$$

If R is less than or equal to 2TB, then the negentropy is very nearly $\frac{R}{2}$[41]. Thus, $\frac{R}{2}$ is/the approximately maximum negentropy possible for the signal which has a given ratio of total signal energy to noise power per unit bandwidth, and it can only be reached if there are at least R sample values available in which to express the signal.

We have already noted that white gaussian noise has a statistically independent gaussian distribution of the same σ^2 in any orthonormal basis system of vectors in function space. Therefore, if we use the wave shape of the desired signal

[38]Ref. [10] pages 85-80 and 102-114.

[39]Ref. [12] p. 589.

[40]In the classical case, if all the energy E were in one degree of freedom, then E/kT would also be analogous to R/2.

[41]When we discuss the ambiguity threshold in the next section, we will show that the organized signal will, in general, become disorganized if it is spread over a number of sample values greater than R.

as one basis vector and if we use a filter which passes only this waveshape of the entire orthonormal set, the output of the filter will have a signal-to-noise ratio given by R. Thus R is the signal-to-noise ratio if all the signal energy has been put into one degree of freedom. It may be shown[42] that this is what is done by the matched filter.

11. Noise Reduction and Thresholds in Communication

A topic which is intimately related to the organization of signals is the question of noise reducing methods of organization in communication systems. Human Beings, without consciously being aware of the fact, use sophisticated methods of noise reduction in both audio and visual perception. The first well-conceived idea of a noise reducing system in communication, however, is probably the invention by E. H. Armstrong[43] of wideband frequency modulation for the purpose of noise reduction.

Detailed discussion of noise reduction in frequency modulation is given in various textbooks[44] but because of the importance of the method as an illustration of a fundamental phenomenon of organization, we shall outline its details here. A signal

$$G(t) = A \sin [2\pi Ft + 2\pi \int s(t)dt] \tag{39}$$

has an instantaneous frequency

$$\frac{1}{2\pi}\frac{d}{dt}[2\pi Ft + 2\pi \int s(t)dt] = F + s(t) \tag{40}$$

The signal G(t) is called a frequency modulated carrier, where F is the carrier frequency and s(t) is the modulation signal. In order to understand the mechanism of F.M. noise reduction, we first consider the case when s(t) is the single fourier component

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[42]Ref. [4] Ch. 4.

[43]Ref. [13]

[44]See Ref. [14] pages 270-280

$$s_1(t) = \Delta F \cos 2\pi\mu t \tag{41}$$

It may then be shown[45] that

$$\begin{aligned} G_1(t) &= A \sin[2\pi Ft + \frac{\Delta F}{\mu} \sin 2\pi\mu t] \\ &= A \Big\{ J_0\left(\frac{\Delta F}{\mu}\right) \sin 2\pi Ft \\ &+ J_1\left(\frac{\Delta F}{\mu}\right) \sin [2\pi(F + \mu)t] - J_1\left(\frac{\Delta F}{\mu}\right) \sin [2\pi(F - \mu)t] \\ &+ J_2\left(\frac{\Delta F}{\mu}\right) \sin [2\pi(F + 2\mu) + J_2\left(\frac{\Delta F}{\mu}\right) \sin [2\pi(F - 2\mu)t] \\ &+ \ldots\ldots\ldots \end{aligned} \tag{42}$$ [46]

The components of the form $\pm J_n\left(\frac{\Delta F}{\mu}\right) \sin [2\pi(F \pm n\mu)t]$ are called sidebands of the carrier $\sin 2\pi Ft$, μ is called the modulation frequency, the coefficients $J_n\left(\frac{\Delta F}{\mu}\right)$ are called the magnitudes of the sidebands, and ΔF is called the peak frequency deviation. In Fig. 7 is a diagram showing the sideband magnitudes in a typical case of wideband frequency modulation. The sideband magnitudes quickly become negligible outside the range ($F \pm \Delta F$). It is therefore customary to consider that there are approximately $2\left(\frac{\Delta F}{\mu}\right)$ effective sidebands. When

$$\frac{\Delta F}{\mu} >> 1 \tag{43}$$

we are dealing with what is called wideband frequency modulation.

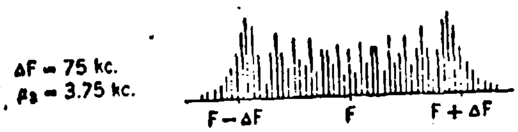

Figure 7

Sideband magnitudes illustrating Equation (42)

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[45] Ref. [14] pages 149-151.

[46] $J_n\left(\frac{\Delta F}{\mu}\right)$ is the Bessel function of the first kind of order n and argument $\frac{\Delta F}{\mu}$.

[47] Ref. [14] pages 272-273.

Suppose that white gaussian noise is superimposed on a wideband frequency modulated signal $G(t)$ of the form (39) and the signal is sent through a transducer, called a frequency detector, whose output is $s(t)$ plus noise. It may be shown[47] that in this case the signal-to-noise ratio is improved as compared with what would be obtained by an amplitude modulation system using the same transmitted signal power and having the same superimposed white gaussian noise. In wideband F.M., the signal-to-noise amplitude ratio is improved by a factor proportional to $\frac{\Delta F}{\mu}$, i.e., proportional to $\left(\frac{\Delta F}{\mu}\right)^2$ in power or energy. The details of the calculation may be found in the cited reference, but we will now examine what makes this noise improvement possible from the point-of-view of organization theory.

In the first place it should be pointed out that an improvement in signal-to-noise ratio is only significant to the extent that it signifies an increase in the amount of information received. For example, suppose that a signal $s(t)$ has superimposed white gaussian noise and the signal-to-noise ratio is 3. If this combination is sent through a device whose output is proportional to the cube of the input, the signal-to-noise ratio in the output would be of the order of magnitude of 27. However, even though the signal-to-noise ratio is increased, the information is unchanged. The probability distributions of the signal and noise amplitudes have been changed and the noise is no longer gaussian, but the negentropy as well as the information content are unchanged. The signal waveshape is distorted by the cubic-law amplifier, and there is no way of using the increased signal-to-noise ratio to regain the signal with undistorted waveshape but with an improved signal-to-noise ratio.

The improvement of signal-to-noise ratio in wideband frequency modulation is, however, informationally significant. It can be obtained without changing the waveshape of the desired signal and with a lower level of background noise in the output.

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[47] Ref. [14] pages 272-273.

Let us compare amplitude versus frequency modulation for the case in which the modulation signal s(t) has a bandwidth μ_o and the peak frequency deviation available for the frequency modulated carrier is ΔF. Then the effective bandwidth of an analogous amplitude modulated signal is $2\mu_o$, whereas the bandwidth of the frequency modulated signal is essentially $2\Delta f$. Let us suppose that the total signal energy and the noise power per unit of bandwidth is the same in both cases, so that Woodward's R is the same for both. Then by Eq. (38) the negentropy represented by a signal with the bandwidth of the amplitude modulated signal is at most

$$2T\mu_o \log\left[\frac{R}{4T\mu_o} + 1\right] \tag{44}$$

whereas a signal with the bandwidth of the frequency modulated signal could possibly have the larger negentropy

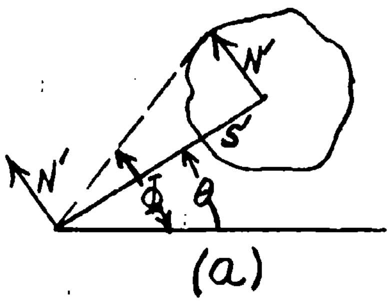
$$2T\Delta F \log\left[\frac{R}{4T\Delta F} + 1\right] \tag{45}$$

assuming that $R > 4T\Delta F$. The actual negentropy in the two cases is not given by Eqs. (44) and (45) but depends on the probability distributions and the constraints in the respective cases.

A comparison of (44) and (45) indicates that a type of modulation might exist in which, for large R, the equivalent $\frac{S}{N}$ power ratio, without waveshape distortion, would increase almost exponentially with the ratio of increase in bandwidth (such as $\frac{\Delta F}{\mu_o}$). We are not, however, interested in the properties of frequency modulation per se, but in the fact that the organization of a signal can be improved by using extra bandwidth in transmission. It is interesting to note that a simple repetition of the signal N times with the same total energy, so that the energy each time is reduced by the factor $\frac{1}{N}$, would give no net gain in negentropy and no improvement

in $\frac{S}{N}$ ratio. Systems which do give $\frac{S}{N}$ improvement by using extra bandwidth (or extra time) without using more energy are somehow able to translate their redundant representation of the signal into an improved organization. Let us examine how this is accomplished in wideband frequency modulation.

The transducer which translates the modulated carrier G(t) in Eq. (39) into the signal s(t) is called a frequency detector.



$$G(t) = S' \sin[2\pi Ft + \theta(t)]$$

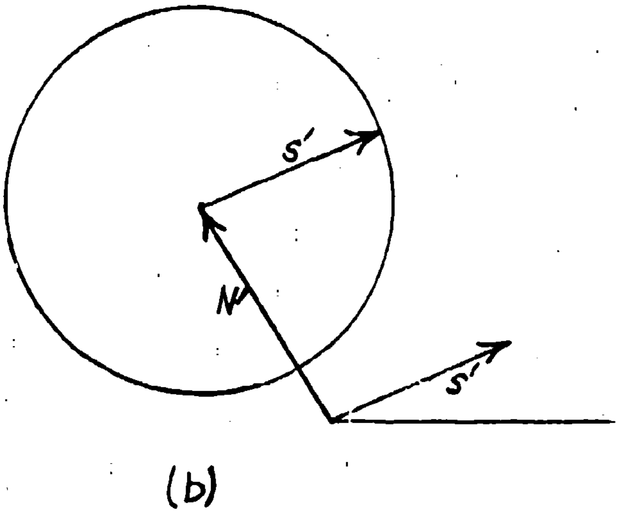


Figure 8

$$n(t) = N'(t) \sin[2\pi Ft + \alpha(t)]$$

If the signal G(t) plus the noise n(t) is represented as

$$G(t) + n(t) = B(t)\sin[2\pi Ft + \Phi(t)] \tag{46}$$

then the output of the frequency detector is

$$\frac{1}{2\pi}\frac{d\Phi}{dt} \tag{47}$$

Part of the mechanism of noise reduction in wideband frequency modulation is illustrated in Fig. 8(a). For a single modulation frequency μ which causes a maximum frequency swing Δf of the carrier, the maximum value of θ (see Eq. 42)

is $\frac{\Delta f}{\mu}$ radians, which can be as large as many complete revolutions. On the other hand, if $\frac{R}{4T\Delta F}>>1$, then the effect of the noise is to cause a change in the angle of amount

$$\Phi - \theta \doteq \tan^{-1} \frac{N'}{S'} \qquad (48)$$

which is small compared with $\frac{\Delta f}{\mu}$. The signal is thus more efficient than the noise in frequency-modulating the carrier. This effect is the first part of the noise reduction mechanism in wideband F.M. The second part is obtained by filtering. If $\frac{R}{4T\Delta F}$ is considerably greater than unity, then only those noise components in the frequency range $(F \pm \mu_o)$ will cause noise modulation in the modulation frequency range. The frequency detecting transducer includes a filter which will not pass any frequencies outside the modulation frequency range. This filter, and the fact that it can eliminate the effects of noise components outside the frequency range $(F \pm \mu_o)$ is the second part of the noise reduction mechanism of wideband F.M.[48]

There is, however, a threshold in F.M. noise reduction. This is illustrated in Fig. 8(b). If $R<4T\Delta F$ so that $(S')^2 < (N')^2$, then the transducer acts so that the noise reduces the signal instead of vice versa, and in addition to reduction in magnitude the signal becomes distorted. These effects become exaggerated as $\frac{R}{4T\Delta F}$ gets smaller. The region in the neighborhood of

$$\frac{R}{4T\Delta F} = 1 \qquad (49)$$

is thus a threshold between noise elimination and signal elimination. When $\frac{\Delta F}{\mu_o}>>1$, it is a sharp threshold.

The existence of a noise reduction threshold is a general phenomenon in virtually all communication systems which use extra bandwidth or extra time for

[48]See Ref. [14] p. 272-273 for a quantitative discussion.

noise reduction purposes, without using extra energy[49]. In the next section, we shall see that an analogous threshold is very important in other organized systems. It was first pointed out by Shannon [9] that a noise reduction threshold phenomenon could be expected in the transformation of the representation of a signal from a function space of higher dimensionality, say $4T\Delta F$, to a smaller dimensional (say $2T\mu_o$) function space. A similar point was made by Woodward[50] during his classical discussion of noise thresholds in radar detection. A function space analysis of noise reduction and threshold for a large class of communication systems is given by Wozencraft and Jacobs[51].

The function space analysis shows, in effect, that in the transformation or mapping from the $4T\Delta F$ dimensional space at the input of the transducer to the $2T\mu_o$ dimensional space at the output, some of the white gaussian amplitude noise at the input is transformed into identity noise in the output. This transformation of amplitude noise into identity noise is dependent upon $\frac{R}{4T\Delta F}$ and rises suddenly from a small to a large value when $\frac{R}{4T\Delta F}$ falls below unity[52]. This is the noise reduction threshold phenomenon.

It is of interest to note that when $\frac{R}{4T\Delta F}$ falls below unity, there is on the average less than one bit of information per system element in the input signal to the transducer. As a consequence of item C in the quotation from Brillouin in Section 9, we would therefore expect that the information could not be extracted. This is quite consistent with the existence of the noise reduction threshold.

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[49] See Ref. [4] p. 623 et seq for a discussion of noise reduction and threshold in pulse-position modulation.

[50] Ref. [10] p. 90.

[51] Ref. [4] Ch. 9.

[52] Lance Whitehead (unpublished) has shown that when the input dimensionality is high, the threshold is sharp. This is a consequence of the mathematical phenomenon that almost all of the volume of a hypersphere of high dimensionality is close to the surface.

The phenomena of noise reduction and thresholds can also be considered from a more elementary point of view in which emphasis is placed upon the mechanism of the noise reduction. In an early paper[53] the present writer has said "When the noise exceeds the improvement threshold value, the signal no longer controls the standard by which coherence is determined and on the basis of which the detector (transducer) is designed to give preferred weighting to the desired signal. Under these circumstances, the detector increases the noise-to-signal ratio rather than the signal-to-noise ratio." In Fig. 8(b), we have seen how control of the standard of coherence in frequency modulation passes from the signal to the noise at the noise improvement threshold.

A detailed examination of systems which use extra bandwidth for noise reduction purposes seems always to show a standard of coherence which is lost when the noise exceeds the improvement threshold. When the signal controls the standard of coherence, the negentropy of redundant signal in the extra bandwidth is efficiently converted by the transducer into negentropy of desired signal. When the standard of coherence is lost, the signal organization collapses.

It is particularly noteworthy that a system which uses extra bandwidth for noise reduction actually increases the effective R of the modulation s(t) in the output signal. By way of contrast, we note that the matched filter does not increase the effective R. The matched filter also does not have a noise reduction threshold. The action of the matched filter is equivalent to a linear operation in function space that transforms the representation of the signal plus noise onto a single system element where the signal waveshape is the basis vector.

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[53] Ref. [12] p. 592.

12. THE SELF-MAINTENANCE OF AN ORGANIZED ACTIVITY BY USING NEGENTROPY ASSIMILATED FROM THE ENVIRONMENT

(a) Introduction

A most important class of organized systems are those which include an organized activity that assimilates negentropy from its environment (i.e., from external sources) in order to maintain itself. A running automobile motor and a biological organism would be examples of such systems. In these systems the organized activity is constantly being attenuated by

(a) Transformation into heat, or

(b) Absorption in a work load, or

(c) Radiation and its analogues.

At the same time, the activity accumulates noise both from its internal operations and from the environment. Negentropy must be assimilated both to replace the attenuation losses and to perform the necessary operations to reduce the noise.

We shall introduce our analysis with the aid of some illustrative examples. We shall not discuss how each point that we make is illustrated in every example, but we hope that the reader will in each case check aspects of the examples. The first five examples represent activities which are reasonably stable over periods of time of interest. The sixth example illustrates the maintenance of a stable activity while travelling in space.

(b) Examples

1. The Clock

We shall consider the case whether the organized activity is either an oscillating pendulum or an oscillating balance wheel. In either case, when the oscillation reaches a certain critical magnitude or threshold, it operates an escapement to release some energy from a lifted weight or

a wound spring to add to the energy of oscillation. This just cancels the attenuation of the oscillation due to the energy lost in controlling the motion of the clock.

2. The Bunsen Flame

The flame of a Bunsen burner has a characteristic size, shape and distribution of color and temperature, which is a function of the gas pressure, the amount of air intake, and the nozzle configuration. The flame is a quasi-stationary activity, but the materials engaged in the activity at any instant are quickly carried away by convection into the surroundings, while the energy leaves by radiation, convection and conduction. The movement of the heated material from the flame draws in new gas and air through the Bunsen burner as well as air from the surroundings, and the combustion of these materials keeps the flame constantly renewed.

The negentropy is taken from the surroundings in the form of gas (say CH_4) and oxygen. This is converted into the flame organization by a pattern of combustion, convection and radiation. We note that in order to get the flame started a certain degree or threshold of the flame's organization must first be reached, such as by putting a lighted match near the nozzle. Once this degree of organization is reached, the flame then proceeds toward its characteristic configuration. If later on, a gust of wind or some other disturbance changes the organization to something sufficiently different from the characteristic configuration, the flame will be extinguished and will not start up again without outside help.

3. The Running Automobile Motor

We shall not go into the details of the organization and operation of the automobile motor. We assume that the reader is sufficiently familiar with them for the purposes at hand. In the case of the running automobile

motor, most of the activity can, of course, be absorbed in a work load.

Just as in the case of the Bunsen flame, in order to get the motor started, a certain approximation to the organization of the motor's operating conditions must first be established by a starting routine. Once this has been done, the motor activity proceeds to its characteristic quasi-stable organization. The motor will continue to run without outside assistance as long as supplies are available in the form of gasoline, etc. to renew the negentropy which is being used up. If, however, some disturbance changes the configuration of the motor's activity to something sufficiently different from its characteristic organization, the motor will stall. Some person or external influence must then carry through the starting routine again in order to get the motor running once more.

We also point out that the waste products of combustion, as well as excess heat in certain locations, represent noise which must be eliminated if the organization is to be maintained. There are also other types of noise which are more involved with the details of the operation.

4. The Electronic Oscillator

In an ordinary amplifier, the output is a magnified replica of the input. In a regenerative amplifier the output is fed back to the input and goes through the amplifier for repeated magnifications. The amount of amplification of the amplifier in one passage, and the percentage of the output which is fed back to the input, as well as the relative phase, are usually all functions of frequency. It is possible to build a regenerative amplifier so that with no input other than its own internal noise of thermal origin, it will have a large output at a chosen frequency. This is an electronic oscillator. Its frequency is determined by its circuit components and connections

The energy and negentropy of the electrical oscillations must constantly be replenished from the power supplies of the oscillator. The oscillator differs from the clock, the bunsen flame and the automobile motor in that it does not have to be started by first establishing an approximation to the organized activity by external means. The components near its characteristic frequency in the background noise are sufficient to start it.

5. <u>The Living Organism</u>

We shall treat the organizational aspects of a living organism at greater length in later sections. At this time we just take note of the fact that the activity of life uses up negentropy which must be replaced by extracting it from food, water and air which is taken in. Among many other means of noise reduction, the living organism has extensive means for the elimination of waste products. Like the flame and the automobile motor, the life activity will be extinguished if its organization becomes too far removed from its characteristic pattern. If the organism dies, it cannot be brought back to life. Within the range of our experience, life activity is always a continuation of previous life activity.

6. <u>Long Distance Communication with Periodic Repeaters</u>

In communication channels which transmit signals between locations which are thousands of miles apart on the surface of the earth, it is common to use what are sometimes called <u>repeaters</u> at periodic locations between the original signal transmitter and the final destination. Thus, when the sending and receiving stations are 2,000 miles apart, repeaters may be located at 200 mile intervals along the transmission path. In the 200 miles between repeaters, the signal is attenuated and is corrupted by noise. At the repeater, the noise is largely eliminated and the signal is amplified to restore its original level. Assuming that the distance between repeaters has been chosen short enough so that the noise does not rise about the noise

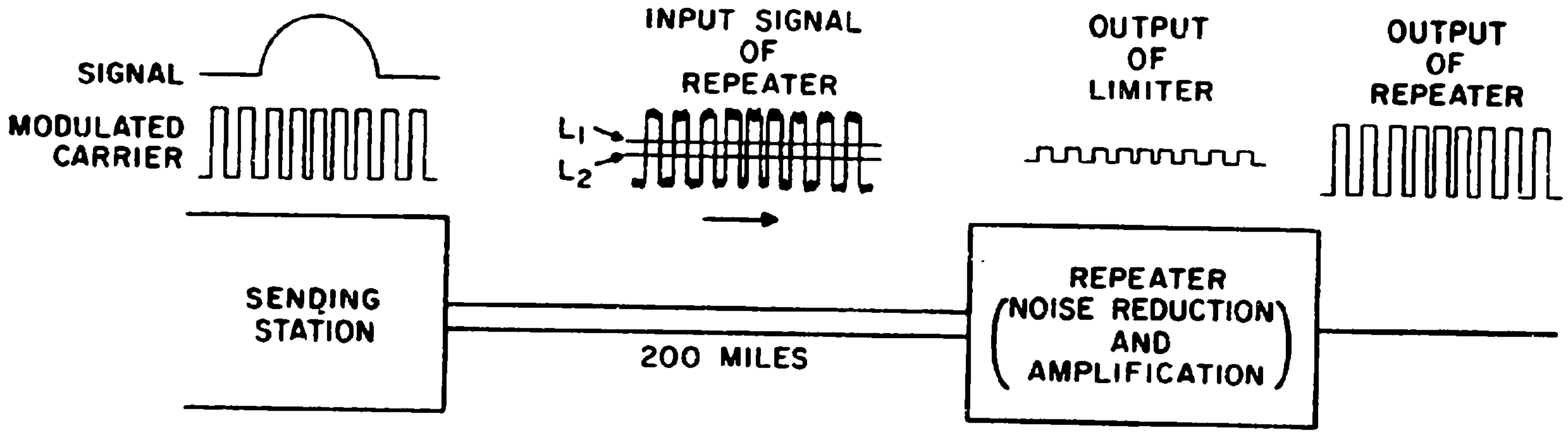
SIGNAL
MODULATED CARRIER
INPUT SIGNAL OF REPEATER
L1
L2
OUTPUT OF LIMITER
OUTPUT OF REPEATER
SENDING STATION
200 MILES
REPEATER (NOISE REDUCTION AND AMPLIFICATION)

Fig. 9

reduction threshold before the repeater is reached, this allows the signal coming out of the repeater to be practically a clean and faithful replica of the original transmitted signal. In this way it is possible to have essentially noise free transmission over thousands of miles.

The particular noise reduction means illustrated in Fig. 9 is the use of pulse frequency modulation. In this case the unmodulated carrier consists of a sequence of equally spaced pulses, for example pulses of 1 mocrosecond duration occurring at a rate of 100,000 pulses per second. Modulation of the carrier is accomplished by changing the pulse rate in accordance with the wave shape of the modulation signal. A large part of the noise reduction is accomplished at the repeater by means of a device called a limiter which passes only the signal which lies between the limits L_1 and L_2 of the input signal. This signal is then amplified up to the level of the original transmitted signal. There are several other aspects of this noise reduction process which we have not discussed, for which we refer the reader elsewhere [14].

We note that the noise reduction threshold is the noise level at which the noise between pulses rises above L_2 or the noise during pulses drives the signal below L_1. This example also illustrates the phenomenon that a quantized signal, such as a pulse, can be made relatively refractory to the effects of small amounts of noise.

The attenuation of the organization illustrated in this example is an attenuation in space rather than in time. It represents a loss of negentropy which is compensated by absorbing negentropy from the power supplies of the amplifiers at the repeater stations. This example is especially instructive because it is so completely understood. It illustrates the

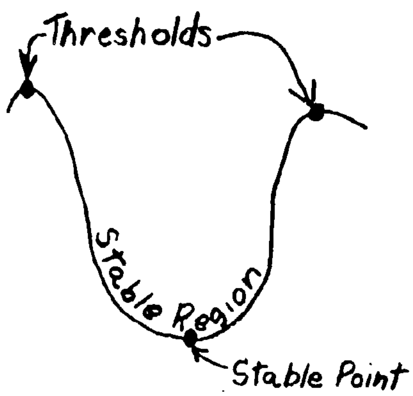

Fig. 10

compensation for attenuation, the noise reduction and the noise reduction threshold which are characteristic of most self-sustaining activities.

(c) Stability

The organized activities in the foregoing examples all exhibited a type of stability which is shown in Fig. 10. It should be emphasized that we are describing a state of activity and not a static condition. This activity may have periodic components, and the state therefore cannot be described in terms of an instant of time, but requires at least a time duration of the longest periodic component. In some representations of the state diagram of the system, the stable point in Fig. 10 may be represented by a closed curve.

Figure 10 is a diagrammatic representation of a state diagram. It shows only a cross section of a multidimensional picture, since the state of the activity typically has many degrees of freedom. A stable point on the diagram represents a stable operating state. Any small displacement of the system from the stable operating state causes a reaction by the system which tends to bring the system back to the stable state. However, in any direction, there is a threshold value to the size of the allowable displacement. If the displacement exceeds this threshold, the system will not return to the stable point. A system which has no such stable point cannot maintain itself in an organized condition.

The existence of the stable state implies that a certain balance exists when the system is in this state, i.e.,

1. Available energy is taken in from the environment as fast as it is used up.
2. System negentropy is taken in as fast as it is used up.
3. Waste products are removed as fast as they are generated.
4. Heat is removed as fast as it is generated.

Small time delays are allowed in these balancing operations, as long as the displacement fluctuations from the stable point caused by the delays do not push the operating state outside of threshold[54].

The state diagram in Fig. 10 is a property of the system constraints. We shall call the state of the system at the stable point an <u>eigenstate</u> of the system of constraints. Alternatively, we may call the entire region around the stable point up to the thresholds an eigenstate of the system of constraints.

As already mentioned, Fig. 10 is diagrammatic of what is meant by a stable state. It implies that the displacement of a system from the stable point causes a reaction by the system which tends to bring the system back to the stable point. There is no <u>a priori</u> guarantee that stable states of activity can be produced. Experience, however, tells us that they can, as illustrated by the examples in Sec. 12b. Le Chetalier's principle in thermodynamics shows that for an isolated system, the equilibrium state is stable[55].

A detailed discussion of a stable state of a specific organized activity is usually very complicated. However, it seems worthwhile to show in at least one particular case how the stability is attained. We therefore, consider the operation of a simplified version of an automobile motor. In Fig. 11, the abscissa represents the horizontal velocity of the car. The ordinate is the torque available from the motor to turn the wheels of the car. It is assumed that the car is moving along a level road of standard paving and that the atmospheric conditions are also standard. The solid curve in Fig. 11 is the <u>torque demand</u> required to maintain the car at a given velocity against the frictional forces of the air, the road and the motor and other internal operating parts. The broken curve in Fig. 11 represents the <u>torque supply</u> from the motor for given settings of the gears and the accelerator. The torque supply rises monotonically with

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[54]Prigogene has shown that in a stable state, the rate of dissipation of free energy is a minimum Ref. [15] Ch. 16.

[55]Ref. [11] page 63.

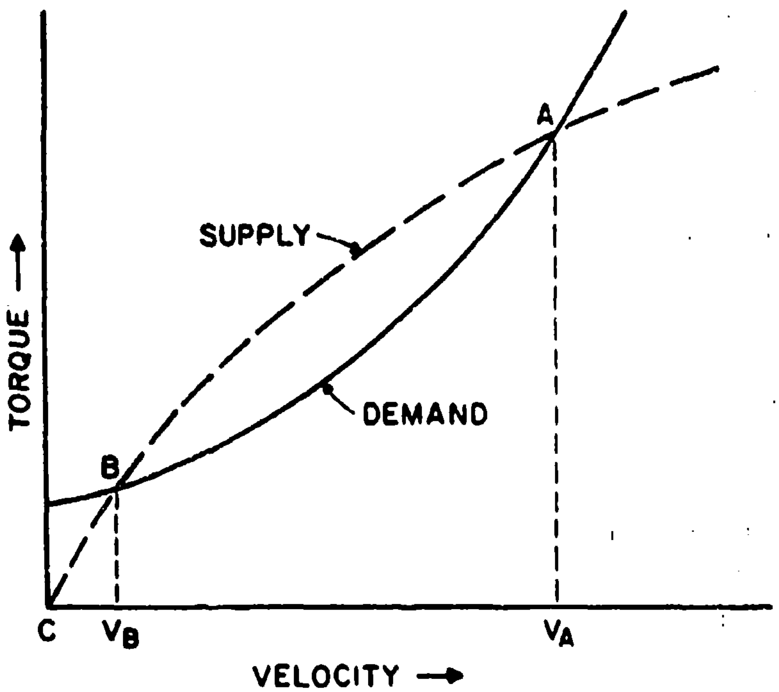

Fig. 11

the velocity of the car, because the rate of fuel intake rises with the velocity of the car. In particular, the rate of intake of fuel (gasoline and air mixture) is proportional to the number of strokes per minute of the cylinders[56] and the number of strokes per minute of the cylinders is proportional to the velocity of the car. For a given setting of the gears and the accelerator, the fuel intake is thus proportional to the velocity of the car. The efficiency of the combustion process, however, varies with the rate of fuel intake so that the broken curve in Fig. 11 is not a straight line.

If the torque supply exceeds the torque demand, the car is accelerated. On the other hand if the torque supply is less than the torque demand, the car is decelerated. Consequently, as long as the velocity exceeds V_B, it will tend toward V_A, which is the velocity specified in the design of the car for the given conditions. If the velocity should fall below V_B, it will tend toward zero. This will cut off the fuel supply and the motor will stall.

From the foregoing discussion, we may draw the following conclusions. A smoothly running automobile motor operates with positive feedback (regeneratively) in its interaction with its nutrient environment i.e., the fuel supply. Thus, as the activity increases, it interacts with the fuel supply to increase the rate of fuel supply which tends to increase the activity still further. On the other hand, operating in the total environment for which it is designed including both the fuel supply and the work to be done, a smoothly running automobile motor operates with negative feedback to stabilize itself at the operating condition, V_A, which corresponds to its design specifications. Thus, if the velocity is less than V_A, the difference between torque supply and demand provides acceleration to increase the velocity. On the other hand, if the velocity exceeds V_A, the difference changes sign so that there is deceleration to diminish the velocity.

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[56] The setting of the accelerator determines the rate of fuel intake per cylinder stroke.

The point A in Fig. 11 corresponds to the stable point in Fig. 10. The Point B corresponds to a threshold[57].

(d) Thresholds

One of the characteristics of an organized activity is that it acts as a transducer to convert negentropy from the environment into its own organization. However, there is a threshold of organization which must be reached before an organized activity can assimilate negentropy from the outside. This may be considered an analogue or perhaps a generalization of the noise reduction threshold which exists for organized signals in communication. In both cases, the threshold represents a dividing region between the loss and acquisition of a standard of coherence. In the signal case the threshold frequently occurs in the neighborhood of the value of one bit of organized activity per degree of freedom. We do not have enough information about other organized activities to know whether the same numerical value is generally associated with the threshold.

Not all organized activities have thresholds. Thus, merely turning on a switch starts the activity of various electrical appliances used in the home and the operation of the switch is unrelated to the level of organization of the activity. The difference here is that activity of these appliances is externally driven and is not self-maintained. The examples in Sec. 12b on the other hand, which did show thresholds, were self-maintained. There are some appliances which are hybrids, being in part externally driven and in part self-maintained. The activity of such appliances can be extinguished and must then be restarted.

The electronic oscillator described in Sec. 12b is self-maintained and it has no apparent threshold. This, however, is misleading. Theoretically a threshold does exist in this case, but the threshold is so close to the $(2 \times \frac{1}{2} kT)$ thermal energy at the natural frequency of the circuit that thermal fluctuations

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[57] The work of Prigogene [16] is pertinent to the present discussion. He shows that stable macroscopic mechanical and chemical activities can arise from microscopic fluctuations provided that a source of available energy is present.

will start the oscillator without any significant time delay, when the power supplies are connected. It thus appears that whenever the activity itself takes part in the transformation of external negentropy into the organized activity, there is a threshold.

The region between the stable point and the thresholds in Fig. 10 may be called the region of stability. This region is determined by the structures and other constraints which determine the organization of the activity. In the design of the system, this region will be made large enough to handle normal fluctuation of the activity, plus a safety factor. Deviation of the actual system from the design specifications of the structures and constraints may be considered a kind of identity or location noise in the system. This noise will cause a contraction in the region of stability by moving the thresholds closer to the stable point. When the noise gets large, there may be no stable region left.

13. SPECIAL METHODS AND DEVICES TO IMPROVE ORGANIZATION

A. The Need for Limiting the Number of Coherent System Elements

Every element in an organized system has a certain amount of noise associated with it. If the noise happens to be white gaussian noise, then the noise power level of the amplitude noise in the system is proportional to the number of system elements. Whether the noise is white gaussian or not, if the number of system elements is so large that the noise level exceeds some noise reduction threshold in the system, then the system is likely to be useless. This is one reason why it is desirable or necessary to limit the number of coherent elements in an organized system.

Location or identity noise provides what is perhaps an even more important reason for limiting the number of system elements between which coherence is

required. In Section 7 it was pointed out that in ordered sets of elements, location noise sets an upper limit to the range over which it is possible to maintain coherence. Whether the elements are ordered or not, we may expect the same type of mechanism to limit the number of system elements between which it is possible to maintain coherence.

The foregoing paragraphs indicate two reasons why the number of elements which can be effectively organized in the same coherent system is limited. The numerical value of the upper limit depends upon the noise level per element of the amplitude and identity noise. Because of this limit, however, the design of large organized systems is usually arranged so as to limit the number of elements between which it is necessary to maintain coherence. Two methods for doing this will be discussed in (B) and (C).

B. The Separation of Activities to Improve Coherence, Specialization

In a large organization or a large project, it is customary to assign the different tasks that must be done to different parts of the organization. This is an example of what we talked about in the preceding paragraph. This relative isolation of separate functions reduces the number of system elements between which coherence must be maintained and tends to reduce confusion and interference. We see examples of it everywhere.

In biological organisms, such as man, this isolation of different functions takes place both in space and in time. The separation in space is indicated by the fact that different organs have different functions. The separation in time is illustrated by cyclic behavior. Very frequently this is a separation into a period of activity, followed by a period of rest and recovery. The physiological activity during the two periods is quite different, as is illustrated, for example, by the very different physiology in the depolarization and repolarization of the heart.

C. Bandwidth Reduction and Its Analogues, Cells

If specialization were described as horizontal separation, then the analogues of bandwidth reduction might be described as vertical separation. The separation of an organism into cells is an analogue of bandwidth reduction. The activity which takes place inside a cell has coherence (organization) between a large number of degrees of freedom. Large as this number is, it is still small enough so that the organization can be kept above the noise reduction threshold. This would not be possible, if it were attempted to operate all the degrees of freedom in all the cells of the body in one coherent organization. Each cell interacts with the rest of the body in terms of a relatively small number of degrees of freedom[58]. Thus, for example, a thyroid cell accepts stimuli for the release of thyroid hormone and responds by releasing the hormone. It also takes in nourishment and releases waste products. It is likely that it also interacts with neighboring cells, in a manner which is not well understood, to coordinate their external structures and activity. These interactions of the cells with the rest of the body are related in a coherent organization throughout the whole body. Since the number of external degrees of freedom per cell is relatively small, it is possible to keep this organization coherent throughout the body[59].

A similar vertical separation takes place in human social organizations, and for the same reasons. Thus, a large company is separated into different levels of organization. The different compartments of the organization are interrelated by a relatively small number of degrees of freedom, as compared with the interrelations between individuals in a given compartment.

D. Redundancy

1. Redundancy for Error Reduction

Since all organizations are subject to stochastic disturbances, it is very common to use redundancy to insure that important things are done. Thus, in the

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[58] It is this reduction in number of degrees of freedom which is the analogue of bandwidth reduction.

[59] The bandwidth reduction actually takes place, at least in part, in more than one step, i.e., from cell to organ and then from organ to entire organism.

body, there are multicellular tissues. If one cell fails to respond to a stimulus applied to the tissue, this is not important as long as other cells do respond. There is even redundancy in entire organs. Thus, there are two eyes,[60] two ears, two lungs and two kidneys. There is also redundancy in type. Thus fat and carbohydrate can both be used as energy sources and when necessary, glucose can be obtained from protein.

2. Redundant Use of the Same Materials and Methods - Standardization

The storage, procurement and training problems of an organization can often be simplified by using the same materials or the same methods for a variety of purposes. This is so well known in human organizations that it is not necessary to elaborate on it. This use of standardization reduces the amount of negentropy (organization) required to accomplish a given task.

It is interesting that in biological organisms, this is also commonplace. Thus, the same amino acids and the same nucleotides are used in the body in a variety of ways. Also the same chemical processes are used in a variety of applications.

E. Monitoring of the Organization and The Environment

Because of the unpredictability of the tasks which an organization may be called upon to perform and the unpredictability of the environment, the state of the organization as well as the environment must constantly be monitored. It is then possible to take corrective action to deal with defects and fluctuations from the normal or stable state, and to prevent the system from being perturbed beyond some disaster threshold.

F. The Use of Carriers[61]

A widespread phenomenon in organized systems is the use of carriers. The vocal chords generate a sound carrier which is modulated in speaking so that it carries a message. Radio and television stations broadcast their programs by

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[60] There are, of course, reasons for having two eyes and two ears other than redundancy.

[61] Ref. [14] Chap. V also Ref. [17]

modulating a high frequency carrier. Trucks act as carriers to transport merchandise. Red corpuscles act as carriers for oxygen and carbon dioxide.

An obviously valuable characteristic of a carrier is that it greatly increases the efficiency and versatility of transportation. However, the selectivity characteristics of carriers are probably even more important, especially from an organization point-of-view. Thus, radio and television broadcasting would be chaos, if the receiver could not choose a particular program by tuning to the carrier. In many cases there are both carriers and subcarriers and after a first selection by tuning to the carrier, there is a second selection by tuning to the subcarrier. This is common in telephonic communication and in pulse modulation systems, but subcarriers also exist in other systems. When merchandise is sent through the mails, the package with the address acts as a subcarrier and the truck, train or plane which carries the packages acts as the main carrier. Without carrier selectivity, transportation would be chaos.

In a very general sense, we can say that carriers set up coherence between distant locations. Another way of describing the action of carriers from an organization point-of-view is to say that carriers carry negentropy from one location to another.

We shall postpone a detailed analysis of the action of carriers until we examine their activities in particular cases of interest.

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APPENDIX II

BIOLOGICAL PROGRAMMING OF GENES AS RELATED TO THE BIOGENETIC LAW AND EVOLUTION

The program of development of a biological organism is inherited from generation to generation. A remarkable characteristic of this program is the "biogenetic law", which states that, "every organism in its development mimics the evolutionary development of its ancestry." This law is evidence for the point-of-view that evolutionary development is fundamentally a consequence of program additions at the end of the preceding program rather than revisions in earlier parts of the program. This does not rule out the possibility of such revisions as a secondary effect.

In our opinion, the foregoing throws doubt on the theory that evolution is a consequence of stochastic mutations and natural selection. Natural selection no doubt causes the extinction of many species. However, the above evidence indicates that evolution probably takes place as a consequence of additions to the DNA to extend the program development. These additions need not take place physically at the ends of previously existing chromosomes. It depends upon the relation of the program sequencing to the physical locations of the activated genes.

The author has reported elsewhere[1] investiga[illegible]wing a consistent similarity between the phenomena of biology and physics. This suggests that just as the development of the motion of a mechanical system is predetermined, on the (ensemble) average, by the laws of quantum mechanics, and the development of any physical system is predetermined on the average by the laws of physics, so also biological evolution is predetermined on the average by laws

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[1] S. Goldman "The Mechanics of Individuality in Nature," Foundations of Physics 1, p. 395 (1971). A continuation article with the same title has been accepted by the same journal.

of biology. Just as in physics, one would expect a statistical distribution in the probabilities of the alternative paths of evolution, but these alternative paths and their probabilities are determined by laws of biology, even though these laws are at present unknown to us. If this is true, then evolution is not a consequence of chance mutations and natural selection in the complete sense that has been generally accepted. It is accordingly doubtful that chance mutations induced chemically, thermally or radiologically are effective in evolutionary development, unless they happen to be part of one of the predetermined evolutionary alternatives mentioned above.

The plant and animal worlds consist of distinct groups, for example, (phylum, class, order, family, genus, and species) and a continuous range of individuals with intermediate characteristics has not been found.[2] This is entirely in accord with the discussion of biological eigenstates in Ref. [1] and the discussion of stability and thresholds in Sec. 12 c & d of Appendix I. The probability that a random mutation would take place which jumps the gap between phyla seems most unlikely even in geological epochs involving billions of individuals. It seems much more reasonable that such a mutation which simultaneously involves a definite pattern of an enormous number of genes would be largely predetermined by the as yet undiscovered laws of the biological analogue of quantum mechanics.

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[2] D'Arcy Thompson, "Growth & Form," p, 1093-1095.